Distributed Control for Tensegrity Robots

Vytas SunSpiral

NASA Ames Research Center

Intelligent Systems Division

1 Motivation and NASA Relevance

Exploration of our solar system increasingly involves physical interaction with the environment, requiring innovation in fields such as robotic manipulation (TA 4.2.1.3: New forms of sample handling, digging, grappling, etc) and extreme terrain access (TA 4.2.1.2: New means of accessing the sides of cliffs, craters, and other extreme locations). In both cases, NASA desires lightweight (TA 12.2.2.1), deployable (TA 12.2.3.1), and reliable devices (TA 12.2.2.3). Thus, the long term goal of this work is to develop actively controlled tensegrity structures and devices, which can be deployed from a small volume and used in a variety of applications including limbs used for grappling and manipulating the environment or used as a stabilizing and balancing limb during extreme terrain access.

Tensegrity structures are composed of axially loaded compression elements encompassed within a network of tensional elements, and thus each element experiences either pure linear compression or pure tension. As a result, individual elements can be extremely lightweight as there are no bending or shear forces that must be resisted. An actively controlled tensegrity structure can be packed into small launch volumes and deployed when required. Active motion in tensegrity structures can be performed with minimal energy expenditure since actuators work linearly along the load paths in the tension elements, avoiding the torques caused by long lever arms.

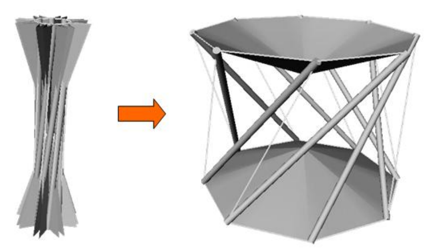

Figure 1: Tensegrity forming a self-deploying satellite antenna [4], another area for potential application of this work

A unique property of tensegrity structures is how they can internally distribute forces. As there are no lever arms, forces do not magnify into joints or other common points of failure. Rather, externally applied forces distribute through the structure via multiple load paths, creating a system level robustness and tolerance to forces applied from any direction. Thus tensegrity structures can be easily reoriented in gravity fields and are ideally suited for operation in dynamic environments where contact forces cannot always be predicted. Likewise, it has been shown that they can be robust to the failure of individual elements, resulting in a gradual reduction of overall workspace, rather than the loss of entire ranges of motion which are common in serial manipulators.

Control theory of tensegrities is at its infancy and is largely focused on shape control, for which there are many open research problems. We believe that the active control problem can be greatly simplified by developing a distributed force control approach. Recent advances in distributed neurologically inspired controls appear to be well suited for controlling tensegrity structures.

1.1 Tensegrity Technical Background

As a form of structural engineering, tensegrity structures are a fairly modern concept, having been initially explored in the 1960's by Buckminster Fuller [8] and the artist Kenneth Snelson [17, 16]. For the first few decades, the majority of tensegrity related research was concerned with form-finding techniques [20, 12, 18, 21] and the design and analysis of static structures [1, 10, 15]. Research into active control of tensegrity structures was initiated in the mid-1990's, with initial efforts at formalizing the dynamics of tensegrity structures only recently emerging [15]. The very properties that make tensegrities ideal for physical interaction with the environment (compliance, multi-path load distribution, non-linear dynamics, etc) also present significant challenges to traditional control approaches. A recent review [19] shows that there are still many open problems in actively controlling tensegrities. These problems are focused on design and form-finding to find stable configurations, shape changing algorithms to find stable trajectories and control methods to compensate for external perturbations.

As can be seen from the list of open problems above, most approaches to active control of tensegrity structures share a common theme of focusing on shape control, likely as a result of the field's initial focus on form-finding. While some work has been done in active vibration dampening [6, 2] it has primarily been focused on controlling nodal displacements, which is still a shape control approach. This focus on shape control complicates the problem because the mapping between forces and position in a tensegrity structure is highly non-linear and often cannot be solved in closed form. We believe that the active control problem can be greatly simplified by developing a distributed force control approach.

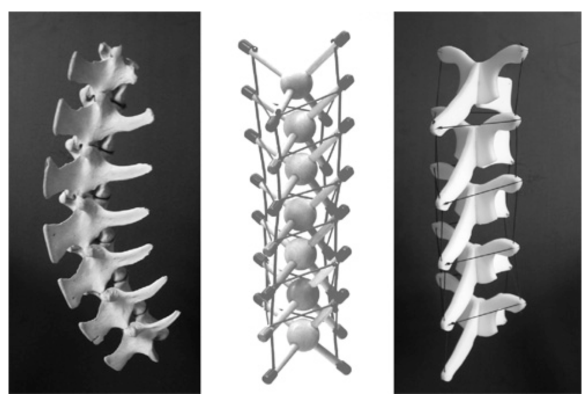

Figure 2: Tensegrity models of the spine showing how vertebrae float without touching [7]

Inspiration for applying such distributed controls comes from another community of researchers who are discovering that biological systems are often built on tensegrity principles. This property is being discovered at all scales, from the cytoskeleton of individual cells [9] to mammalian physiology [11]. A growing group of researchers, medical doctors, physical therapists, and surgeons [3] are realizing that the common sense view of our skeletal structure as the primary load bearing elements of our bodies is flawed. In the emerging biotensegrity model, bones are still under compression, but they are not passing compressive loads to each other, rather it is the continuous tension network of fascia (muscles, ligaments, tendons) that is the primary load path for forces passing through the body. Recent anatomical research through fresh dissections (i.e. without preserving the cadaver, a process which changes the fascia) [13] is providing evidence of the global network of continuous connective tissue that manages force transfers in the body [14].

The purpose of discussing the biological aspects of tensegrity structures is two fold: as an indication that such structures are well suited to active physical interaction with the dynamic world, and as a source of inspiration for novel control schemes. Specifically, it is theorized that mammalian motion control can be described as an inner force based decentralized controller located in the spine, driven by an outer-loop position based controller located in the motor cortex. The value of this two layer control hierarchy is that it provides a massive reduction in the dimensionality of the shape control problem. Instead of solving for the non-linear relationships between elements, shape control is simplified to simply applying fictitious control force vectors in cartesian space onto the underlying distributed force control system. This ”drives” elements of the structure towards the desired location while the rest of the structure automatically maintains dynamic stability to support the motion. This approach also allows force control to be the primary integration point between structure and environment, a requirement which has become apparent to modern robotic systems such as Robonaut 2. [5].

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